Thermally induced nonlinear mode coupling in high power fiber amplifiers

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Thermally induced nonlinear mode coupling in high power fiber amplifiers

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Abstract: Thermally induced nonlinear mode coupling leads to transverse mode instability (TMI) in high power fiber amplifiers. A numerical model including altering mode profiles from thermal effects and waveguide perturbations predicts a TMI threshold of ~200W.
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1. Introduction

The recent increase in extracted output power from rare-earth doped fiber amplifiers has led to observations of transverse mode instability (TMI) above a system and fiber dependent average power threshold [1-3]. TMI results in rapid beam fluctuations, typically between the fundamental mode (FM) and the first higher order mode (HOM), on a ms timescale that significantly degrades beam quality and constitutes a significant impediment to future power scaling of fiber amplifiers. The quantum defect of the gain medium results in fiber heating at high average power, causing a thermally induced long period grating (LPG) due to mode beating. Power is transferred from the FM to the HOM by this LPG and can be described by a nonlinear gain coefficient χ, which may depend on position along the fiber [4]. The nonlinear gain is shown to increase with increasing heat load due to the thermo-optic effect since the thermal perturbation of the fiber results in increased overlap between the modes. In this work we numerically model the nonlinear power transfer and estimate the TMI threshold, when taking temperature and mode profile evolution along the fiber into consideration.

2. Theory and results

A Yb-doped rod fiber amplifier (285/100) with the cross-section in Fig. 1(center) is considered. The thermally induced mode profile change is modeled along the fiber by solving the steady-state heat equation assuming a uniform heat load Q across the rare-earth doped region [5]

$$Q(z) = g(z)\frac{P_1(z)A_{core}}{A_{eff,1}}\left(\frac{\lambda_s}{\lambda_p}-1\right). \tag{1}$$

The signal power and gain g along the fiber amplifier is modeled by a simple amplifier model. The local modes of the fiber are then calculated using a numerical finite element modesolver.

A set of nonlinear coupled-mode equations describes the evolution of the mode power of the FM, P_1, and HOM, P_2 [4]. The HOM power is governed by

$$\frac{\partial p_2}{\partial z} = \left[\Gamma_2 + \chi(z,\Omega)P_1(z)\right]g(z)\left|p_2(z,\Omega)\right|^2, \tag{2}$$

where p_2 is the scaled mode amplitude $p_i = \sqrt{n\varepsilon_0 c/2}A_i$, n is the refractive index assumed equal for both modes and the material, ε_0 is the relative permittivity, c is the speed of light and A_i is the mode amplitude. Γ_i is the mode overlap with the active region. χ is the nonlinear coupling coefficient that depends on z-position and the frequency difference Ω between the FM and HOM, see Fig. 1(center). The initial FM power $P_{0,1}$ is amplified by the rare-earth doping giving the FM power $P_1(z) = P_{0,1}\exp\left[\int_0^{z'}\Gamma_1(z)g(z)\mathrm{d}z\right]$. The power spectral density (PSD) of the HOM in Eq. (2) is written on the form

$$\left|p_2(z,\Omega)\right|^2 = f(z,\Omega)\exp\left[\int_0^{z'}\Gamma_2(z)g(z)\mathrm{d}z\right], \tag{3}$$

where f describes the modal gain through FM power transfer, and the exponential is the gain from the active material. Inserting this expression in Eq. (2) and solving with respect to f, yields

$$f(z,\Omega) = f(0,\Omega)\exp\left[\int_0^{z'} \chi(z,\Omega)P_1(z)g(z)\mathrm{d}z\right] = f(0,\Omega)\exp\left[\int_0^{z'} \tilde{g}(z,\Omega)\mathrm{d}z\right], \qquad (4)$$

where $f(0,\Omega)$ is the HOM input PSD and the exponent corresponds to an effective gain coefficient $\tilde{g}$, yielding nonlinear mode coupling. χ is an odd function approaching zero as Ω tends towards zero, see Fig. 1(center), therefore there must be a seed to initialize power transfer from the FM to the HOM. Assuming this to be relative intensity noise R_N from the seed laser the HOM input PSD is $f(0,\Omega) = P_{0,2}\delta(\Omega) + 1/4\, R_N(\Omega)P_{0,2}$ [4]. This is inserted in Eq. (3) together with Eq. (4) to find the HOM PSD along the fiber amplifier:

$$|p_2(z,\Omega)|^2 = \left\{P_{0,2}\delta(\Omega) + \frac{1}{4}R_N P_{0,2}\exp\left[\int_0^{z'} \bar{g}(z,\Omega)\mathrm{d}z\right]\right\}\exp\left[\int_0^{z'} \Gamma_2(z)g(z)\mathrm{d}z\right] \qquad (5)$$

Integrating over all frequencies yields the HOM power P_2, which can be expressed in terms of HOM content ξ and using the expression for the heat load in Eq. (1)

$$\xi(z) = \xi(0)\exp\left[\int_0^{z'} -\Delta\Gamma(z)g(z)\mathrm{d}z\right]\left\{1 + \frac{R_N}{4\left(\lambda_s/\lambda_p - 1\right)}\int_{-\infty}^{\infty}\exp\left[\int_0^{z'} \chi(z,\Omega)Q(z)\frac{A_{core}}{A_{eff,1}(z)}\mathrm{d}z\right]\mathrm{d}\Omega\right\}, \qquad (6)$$

where $\Delta\Gamma = \Gamma_1 - \Gamma_2$. The HOM content is computed for increasing pump powers keeping the seed power constant at 10 W. Fig. 1(right) shows the HOM content for increasing signal power. The HOM content increases abruptly, indicating a TMI threshold at ~209 W – 253 W of signal power depending on the RIN. The TMI threshold has also been estimated when neglecting thermally induced waveguide perturbations yielding higher TMI threshold values of 180W – 270W. The longitudinally changing nonlinear coupling coefficient thus significantly affects the nonlinear power transfer, resulting in a lower TMI threshold.

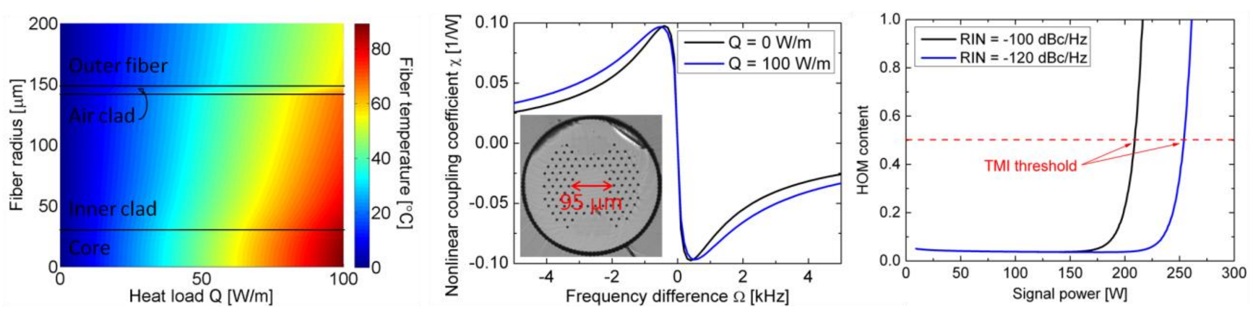

Fig. 1. (Left) Fiber temperature as a function of heat load Q. (Center) The nonlinear coupling coefficient as a function of FM and HOM frequency difference Ω for Q = 0 and Q = 100 W/m. (Right) The calculated HOM content as a function of signal power. TMI threshold is estimated at ~209W – 253W depending on relative intensity noise (RIN).

3. Conclusion

Nonlinear power transfer between the FM and HOM resulting in TMI has been numerically modeled. Including the thermally induced waveguide changes along the fiber amplifier provided a realistic estimate for the obtainable extracted output power of ~209W – 253W before TMI sets in.

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